

AIR FORCE REUSABLE BOOSTER SYSTEM

A QUICK-LOOK, DESIGN FOCUSED MODELING AND COST ANALYSIS STUDY

Edgar Zapata
National Aeronautics and Space Administration
Kennedy Space Center, Florida

ABSTRACT

This paper presents a method and an initial analysis of the costs of a reusable booster system (RBS) as envisioned by the US Department of Defense (DoD) and numerous initiatives that form the concept of Operationally Responsive Space (ORS). This paper leverages the knowledge gained from decades of experience with the semi-reusable NASA Space Shuttle to understand how the costs of a military next generation semi-reusable space transport might behave in the real world – and how it might be made as affordable as desired. The NASA Space Shuttle had a semi-expendable booster, that being the reusable Solid Rocket Motors/Boosters (SRM/SRB) and the expendable cryogenic External Tank (ET), with a reusable cargo and crew capable orbiter. This paper will explore DoD concepts that invert this architectural arrangement, using a reusable booster plane that flies back to base soon after launch, with the in-space elements of the launch system being the expendable portions. Cost estimating in the earliest stages of any potential, large scale program has limited usefulness. As a result, the emphasis here is on developing an approach, a structure, and the basic concepts that could continue to be matured as the program gains knowledge. Where cost estimates are provided, these results by necessity carry many caveats and assumptions, and this analysis becomes more about ways in which drivers of costs for diverse scenarios can be better understood. The paper is informed throughout with a design-for-cost philosophy whereby the design and technology features of the proposed RBS (who and what, the “architecture”) are taken as linked at the hip to a desire to perform a certain mission (where and when), and together these inform the cost, responsiveness, performance and sustainability (how) of the system. Concepts for developing, acquiring, producing or operating the system will be shown for their inextricable relationship to the “architecture” of the system, and how these too relate to costs. Design and technology features bear special relevance to early program research and development directions. Given the uncertainties involved in both their actual performance promise and their relation to costs of operational systems, this later relationship is also given special attention.

INTRODUCTION

Estimating the cost of complex, expensive, new technology, fulfilling some need and making abundant promises, has not proven to be an easy task for the US government and its private sector aerospace industry. Relatively independent reviews over the years, addressing the state of affairs in everything from cost estimating, to cost control, from specific projects to trends, have highlighted time and again very significant deficiencies in cost estimating. These shortcomings in process, organization or controls lead to cost over-runs, delays and program cancelations.

Consider a recent report by the Government Accountability Office regarding DoD Weapons systems:

¹Since 2008, DOD's portfolio of major defense acquisition programs has grown from 96 to 98 programs, and its investment in those programs has grown to \$1.68 trillion. The total acquisition cost of the programs in DOD's 2010 portfolio has increased by \$135 billion over the past 2 years, of which \$70 billion cannot be attributed to quantity changes. A small number of programs are driving most of this cost growth; however, half of DOD's major defense acquisition programs do not meet cost performance goals agreed to by DOD, the Office of Management and Budget, and GAO. Further, 80 percent of programs have experienced an increase in unit costs from initial estimates; thereby reducing DOD's buying power on these programs."

Similarly, recent (2009) critique of a much smaller agency such as the National Aeronautics and Space Administration (NASA) is not hard to find:

²GAO assessed 18 NASA projects with a combined life-cycle cost of more than \$50 billion. Of those, 10 out of 13 projects that had entered the implementation phase experienced significant cost and/or schedule growth. For these 10 projects, development costs increased by an average of 13 percent from baseline cost estimates that were established just 2 or 3 years ago and they had an average launch delay of 11-months. In some cases, cost growth was considerably higher than what is reported because it had occurred prior to the most recent baseline."

It is taken as a given that the participants in large-scale, complex, technologically challenging programs and projects, leaders, managers, and cost estimators alike, would all like to improve the viability of the tasks they wish to see succeed. It is the goal of this cost analysis of a future, proposed, Reusable Booster System for launching payloads to space, to develop a more productive set of insights into costs and their relation to decisions along the way. These insights should connect to decisions, about designs, technology and investments, and the method behind the cost analysis should scale, and generate even more insights along the way.

RESULTS AND DISCUSSION

CONTRASTS IN COSTING

In any profession, the matter of causality is a significant part of making decisions. If a healthcare provider knows that eating salty foods can cause blood pressure to rise, then the reduction of salt in the diet will be part of trying to lower a person's blood pressure. In estimating, the costs of developing, making or operating a certain system, program/project managers also seek out causality. Unfortunately, a decision maker's repertoire of decisions, their authority, and a host of external circumstances may work to remove many cost drivers from the range of options available to the patient. Further complicating matters, the causality between costs and the system dreamed of is easily lost in the fog of war.

Consider the example of creating an X-Y plot of the weight and cost of previously developed systems. Figure 1 shows a series of data points relating the mass and the cost of development of past rocket engine programs. Naturally, this type of regression analysis leads to the infamous "weight based" cost estimating debate. Here, given the weight of a needed engine design, the expected cost can be closely estimated as if to say – "if the engine being planned, is developed in practice like these were, by similar heritage and similarly experienced organizations, applying similar technology, etc, then the cost will similarly be Y" (approximately).

The "etc", ground-rules, assumptions, technical minutia, and caveats that fill out the prior phrases are endless and nuanced, yet having that quick answer on costs is useful in only the most limited of ways. ³Complexity is a hidden variable in these types of causality debates, but since a regression fit is often so good, that point is often lost in the fray caught up in just bounding some number. The importance of understanding the question is lost.

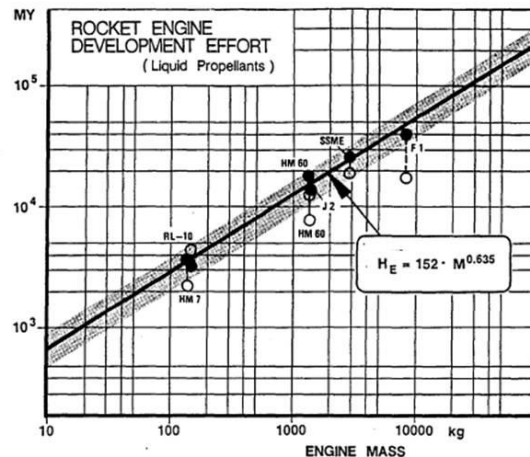


Figure 1: Engine mass vs. cost of development effort, from the descriptive cost model and data of “⁴Transcost”, D. Koelle, 2000

Alternately, there exist some very sophisticated ways of going about complex systems cost estimates. These processes are mature enough to leave an outside observer or decision maker with ample confidence that given the right resources, the project can perform close to as promised (albeit, not at the costs advertised, as seen in previous evidence). A Design Structure Matrix approach is one such method that is very useful throughout the phases of a products development and into mission operations. One aspect of such an approach, begging improvement, is the direct connection back to the same, singular product everyone wants, for everyone on the team. That connection is not as singular. As shown in Figure 2, and taking as an example a desire for a certain reliability in an RBS (because of a desire for readiness, availability, mission success, etc), analysts down the DSM loop will have a more distilled view of requirements the further down the structure they find themselves. The real world “thing” is a whole, and what a user wants’ of it does not change, begging the question of how a more direct connection to that desire can be shored up in the process, and would such an improved connection be of benefit?

Contrasts in analysis approaches, keeping in mind the view of participants, back to the desired outcome, are important. The probability of a projects cancelations or having a false start could conceivably be significantly reduced, if up-front insight improves the connection between what is wanted (goals, requirements, turn-times, system availability, etc), its possible costs, and the design decisions available in any phase of the project.

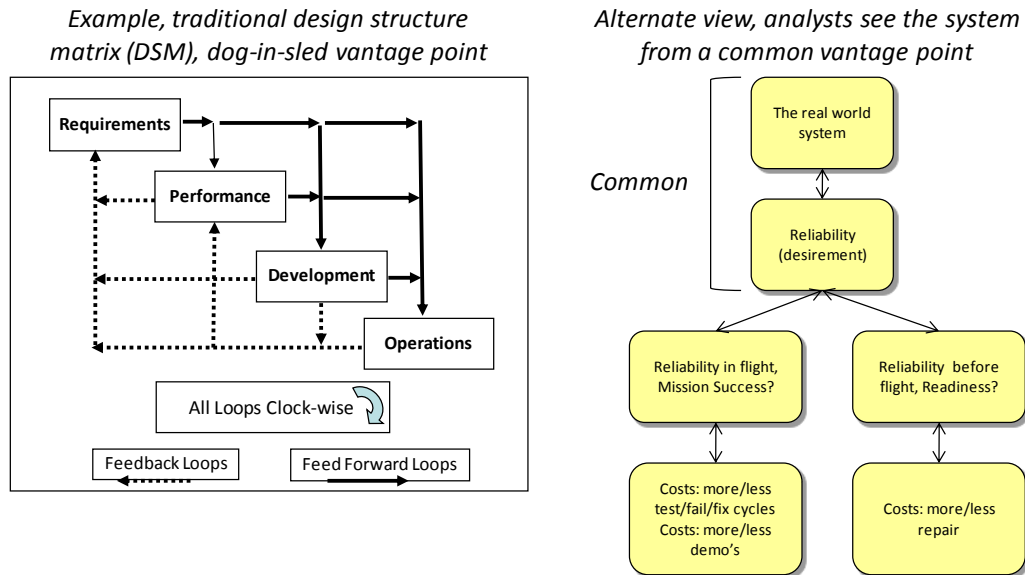


Figure 2: The singular product everyone wants, and every analyst, decision maker, or organization plays a role in, has singular qualities that affect everyone as well, just in different ways.

COST STUDY APPROACH

The approach taken in this quick-look study is about methodology and testing that method using a model, with an emphasis throughout that leans to the alternate view (the right side) of Figure 2. Additionally, the thought is to examine reusable booster systems as regards a range of potential cost scenarios across a range of potential design choices. This is akin to a sensitivity analysis on the dials and knobs of a model, with the model representing the choices and tangible actions that exist in the real world. These choices will lead to a certain life-cycle cost picture.

INFORMATION STRUCTURE

What is a strategy, an architecture, or a goal can all be easily muddled when the responsible parties from engineering and technology circles analyze, discuss, advocate and justify a projects direction. The information structure in Figure 3 helps assure at the start of the exercise that we have a common picture formed around the questions, as well as the answers. Any analysis should return to its information structure in an iterative way once generating useful information.

Why, Where, When, How, Who and What set the borders for where applicable information fits. The RBS system's turn-time is part of "When" in the mission (being about time), as one example.

Information Structure

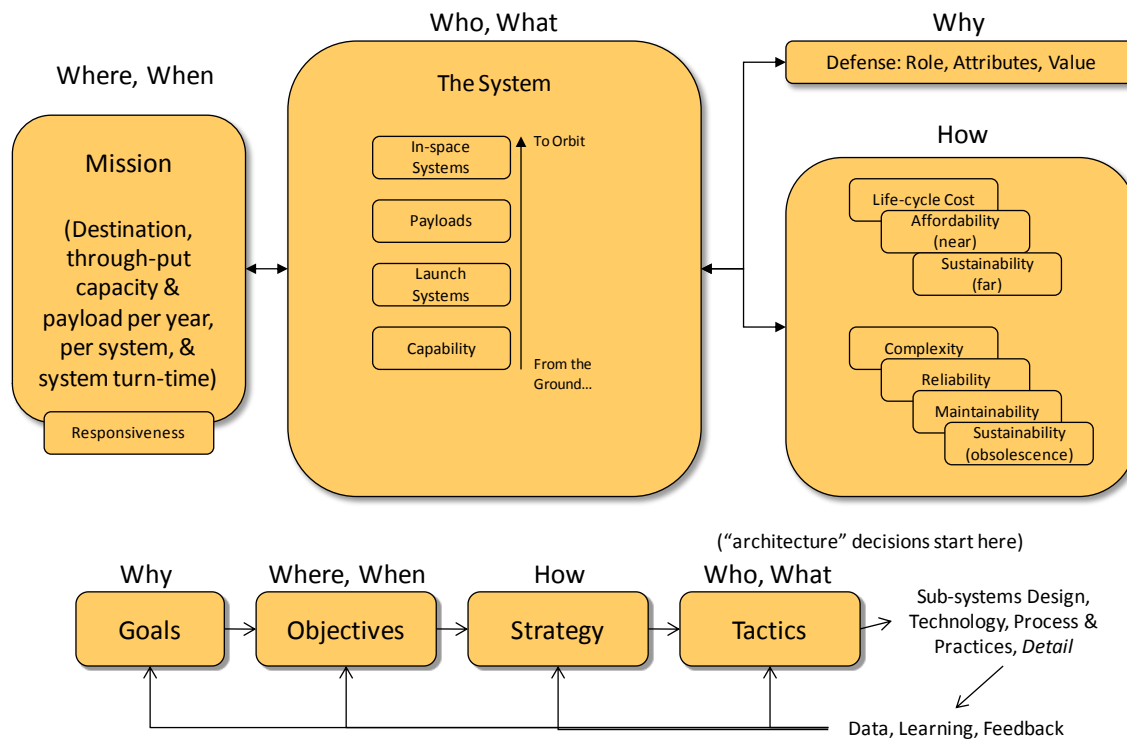


Figure 3: The high level Information Structure for this analysis

SCOPE OF THE SYSTEM

Comprehensiveness is important in a cost analysis at the architecture level of boosters, stages, facilities and organizations. Forgetting to understand or mention the items excluded in an analysis sets the stage for providing a misleading cost estimate. Figure 4 shows a comprehensive view of the world of a large scale project, one where everything from the earliest of R&D, to the eventual replacements, from the most direct hands-on, to the most in-direct support, is all included.

For purposes of the analysis at this stage, some items are excluded (as indicated) that have little likelihood of being distinguishing features from fully expendable launch systems as compared to the RBS system to be looked at (in this stage of analysis). A support wing for example, providing for generic infrastructure needs (electrical, transportation, etc) would fall in this category. The payload to go into the system (the satellite, payload, instruments, etc) also falls into this category of "all other things being equal" (for this stage in the analysis).

MODELS

A model is a very elaborate thought experiment. A good experiment is informed, or made more "real", by connections to real world experience. Real data, as part of the models basis of calculations, and outputs that stand-up to sanity checks, are necessary parts of a cost model. The goal is to be informative, and not just an endless series of guesses. Getting real world data into a model, and getting outputs that "make sense", all without excessive forcing, calibration, or assumptions (those guesses) leads to a model that is useful in figuring out how the real world thing of interest might actually behave.

Various model candidates were reviewed for this exercise, knowing there was strong desire to (1) see RBS-like design features as model inputs, (2) generate a life-cycle cost picture, inclusive of non-recurring and recurring expenses, (3) connect the former two areas. The resulting model is an unfinished but functioning hybrid, a mix of the KSC⁵ Launch & Landing Effects Ground Operations (LLEGO) model with a budgetary, life-cycle cost model similar to those used in NASA exercises. The screens in Figure 5 show an example open series of MS Excel tabs and LLEGO software working together in this hybrid when performing a sensitivity analysis.

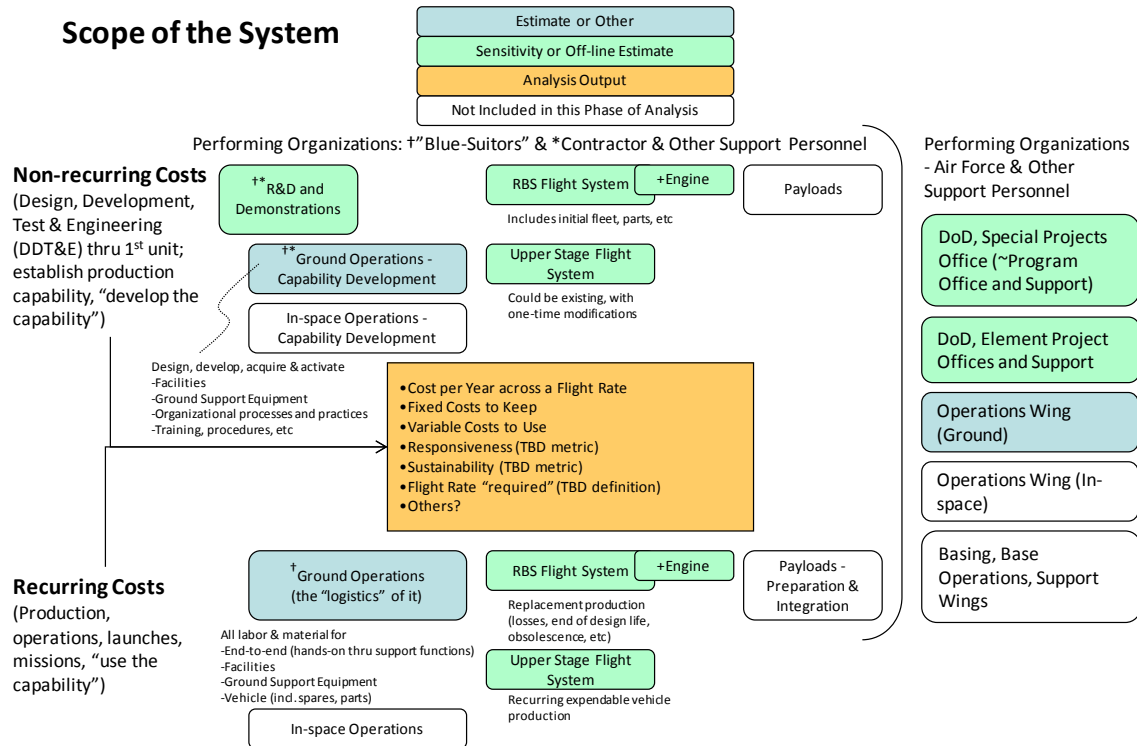


Figure 4: Scope of the RBS System

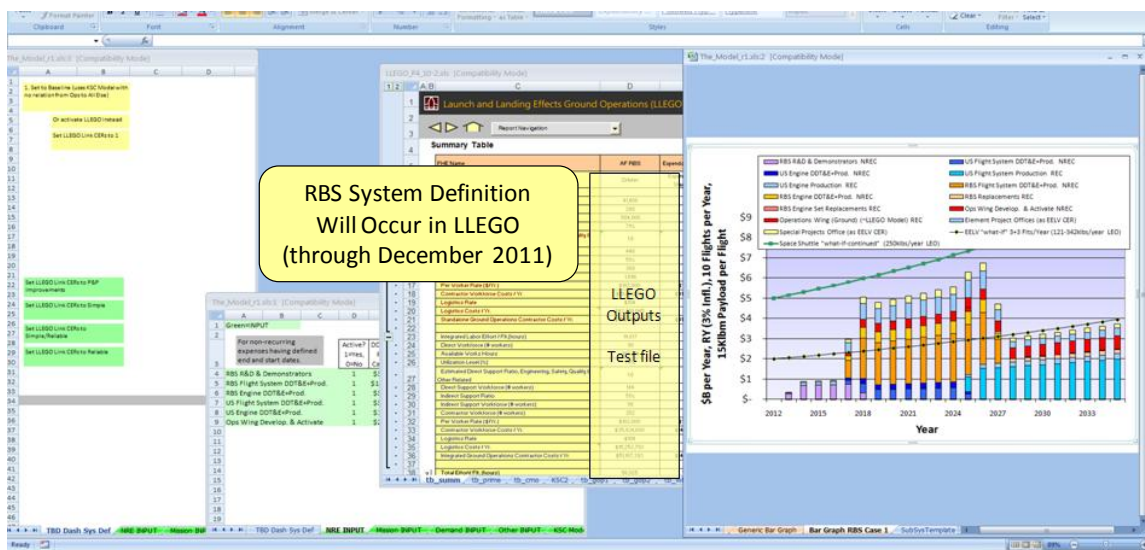


Figure 5: Mixed LLEGO/Life-Cycle Cost Model Screen Shot

THE REUSABLE BOOSTER SYSTEM – A CONFIGURATION

Since this analysis is as process centric as it is focused on results pointing the way to further develop the cost analysis approach and methodology, the RBS configuration chosen for analysis will be referred to simply as “A Configuration”. There is no pretense here that the configuration chosen for this analysis is a baseline, or a reference flight system. Reusable Booster System configuration information useful for cost modeling and analysis is lacking. At this stage, the available RBS architecture information lacks sub-system and process design detail. Where sub-system insight is available (i.e., the ⁶KSC/AFRL RBS CONOPS”), it is for guidance, defining design and technology expectations consistent with an efficient turnaround operation. The information available is not “closed”, where a single set of consistent, comprehensive, cost, architecture, sub-systems, performance, risk and reliability information has come together, all in one place, defining one vehicle.

The result for the RBS configuration in this analysis was a merged information set based on numerous sources. The concepts scoured for information for this analysis are in the 15,000 lbm to low-Earth-orbit class, and are all hybrids using a reusable booster stage with an expendable 2nd stage. While the information gathered may be inconsistent on many counts (such as the placement of the upper, 2nd stage, atop or below the reusable booster) it is routine practice, if not ideal, to take this mix-and-match approach to information. Mixing and matching diverse configuration information is less than ideal, akin to “rubberizing an engine” or “scaling”. The method does allow useful analysis. Since much of the emphasis here is the method of analysis, this mix of configuration data available is adequate.

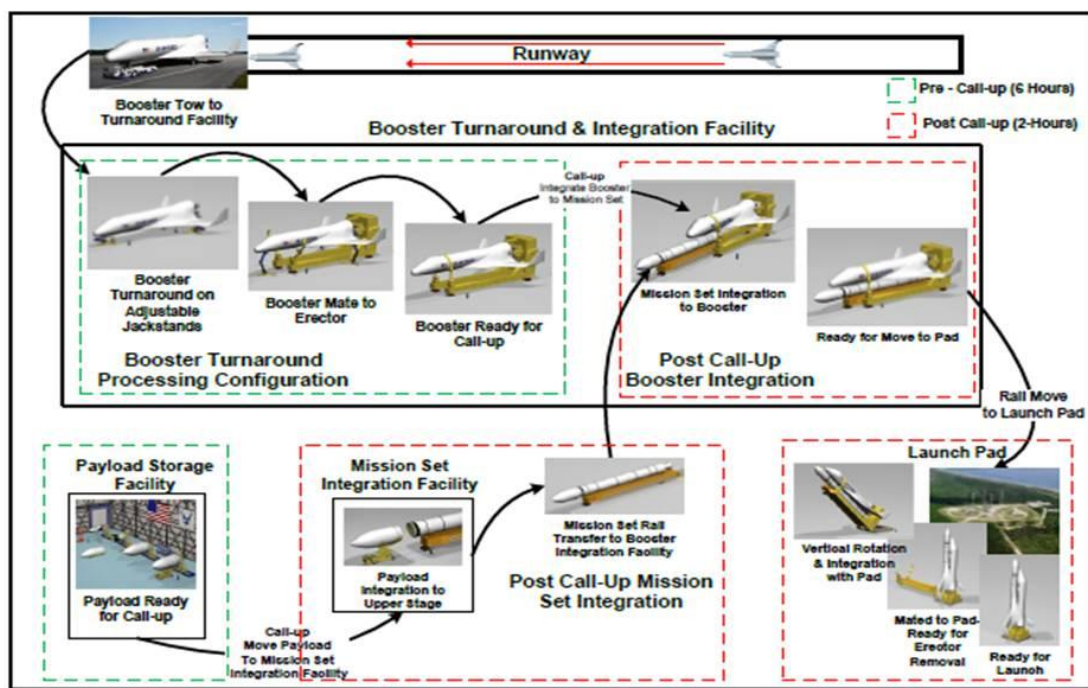


Figure 6: A 15,000lbm payload configuration, from the KSC / AFRL Concept of Operations (CONOPS) document

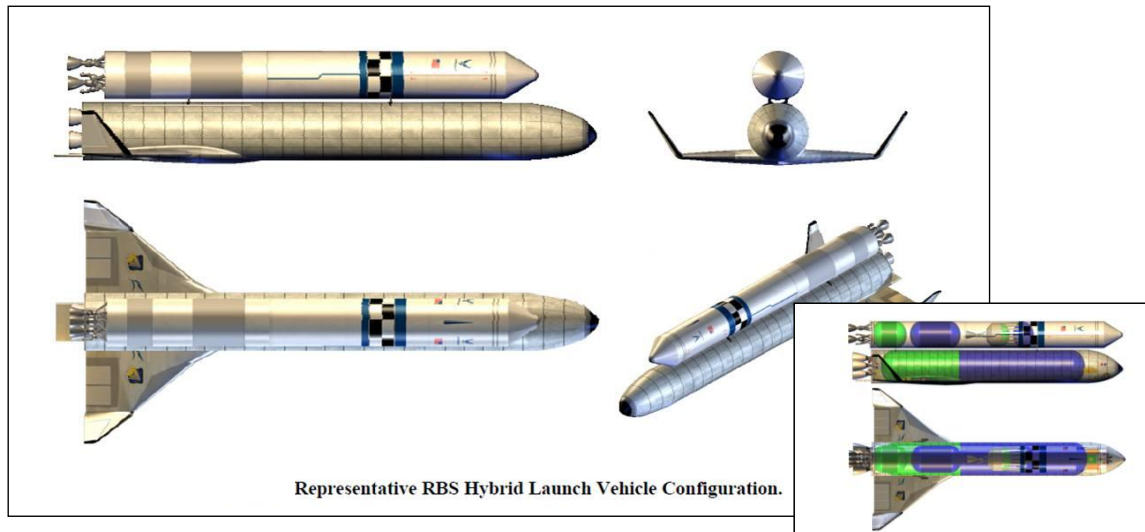


Figure 7: A 15,000 lbm payload configuration, as examined in “⁷Return to Launch Site Trajectory Options for a Reusable Booster without a Secondary Propulsion System” by Bradford & Hellman

PRELIMINARY MODEL AND ANALYSIS RESULTS

The steps in this analysis were as follows:

- Step 1 – Choose the starting point cost inputs or baselines, excluding the wing operations (ground operations through launch).
 - Values taken from the ⁸literature, or where lacking as rough-orders-of-magnitude based on analogs.
 - Initial inputs taken in complete isolation.
 - No inter-relationships to the LLEGO / Ops wing effort, operability, improvements, or greater design co-relations.
 - Start with a small fleet of 10 Reusable Boosters, segueing from Design, Developmentm Test & Engineering (DDT&E) and production setup, into actual production and missions in the mid-2020's.
 - A fleet of 15 by 2035.
- Step 2 - Complete the picture with an estimate from the model & analysis (LLEGO) for the wing operations of a basic, simplified reusable booster.
 - Taking a Space Shuttle Orbiter baseline in the model-
 - Change dimensions (nominal)
 - Delete numerous sub-systems
 - Payload, Crew, Windows, RCC, HRSI, Fuel Cells, Water Spray Boilers, Active Thermal Control Heat Exchangers, OMS.
 - All the fluids, tanks and engines of these systems (waters, Fuel Cell Grade LOX, Fuel Cell Grade LH2, assorted GN2 & GHe for pressurization, NH3, Freons, OMS Bi-propellant Hypergolic fluids, etc).
 - Keep other basic systems (RCS, Landing Gear, Hydraulics, Avionics, etc).
 - Add/adjust for internal LOX/RP tanks, batteries (not APUs), etc.

- Lastly - Step 3 – Co-relate the design aspects from the LLEGO sub-systems centric view across the cost phases.
 - Strengthening the relationship between near term, non-recurring costs, and far term recurring costs and flights.

The most important step is the last step. By considering the relationships between later, far term outcomes, such as operations, and previous steps such as development, or production acquisition, the intent of quantitatively making the leap directly from one to the other begins. While any team of analysts should implicitly maintain such connections using traditional analysis methods (as in the left part of Figure 2) the intent here is to more explicitly have the connections sync and drive the analysis.

Traditional methods of synchronizing data, inputs, or information, with configuration control, data dictionaries, master schedules, a schema's or ontology, are very much about trying to control the flood of diverse information and synchronize it among many users. Those users are analysts, including costs, with very diverse data needs.

The leap here is to stay targeted on an RBS system goal, such as affordability, operational costs, and the responsiveness inherent in such goals, and allow the drivers there to propagate backwards into the system design and into the cost of other phases. The near term costs of any project are assumed as important as the later operations phase, defining a life-cycle that on balance obtains some value, such as an RBS system that performs a function that stakeholders must have.

The following in Figure 8, Figure 9, Figure 10, and Figure 11 are some early results of this methodology, running assorted sensitivities around the drivers of (1) design, (2) reliability and (3) organizational processes and practices.

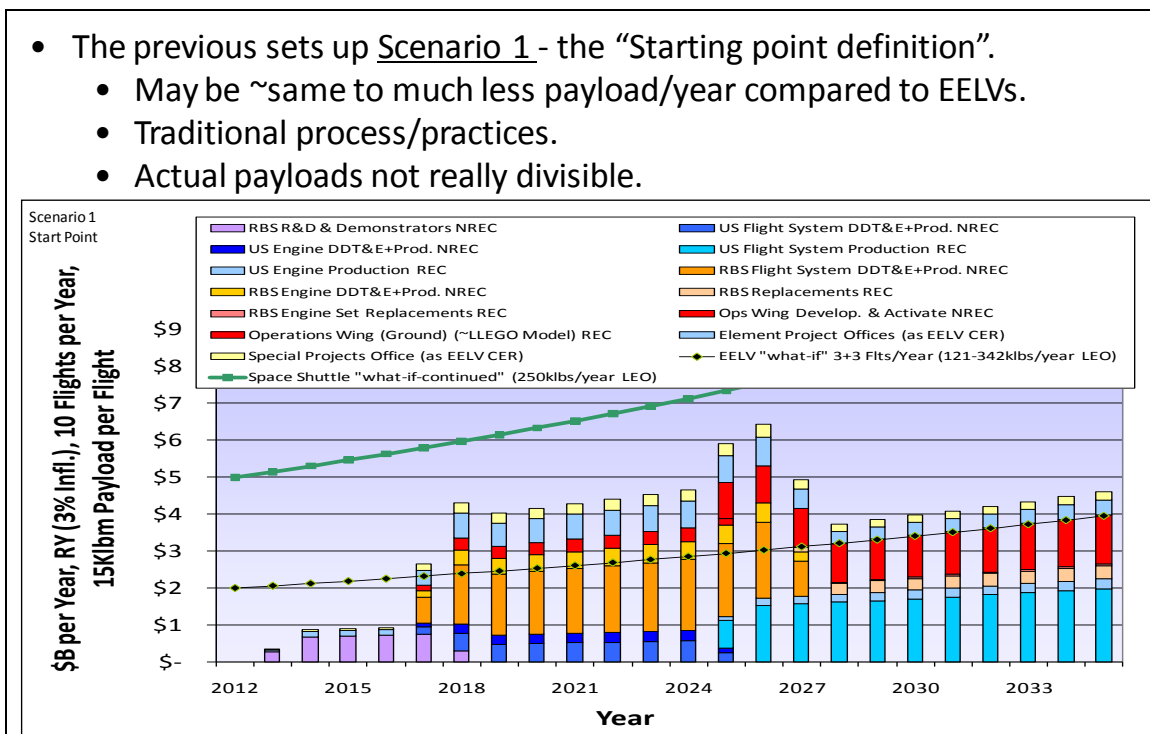


Figure 8: Scenario 1 Life-Cycle Relations

- Scenario 2: The simplifications in the reusable booster design are further co-related as up-front simplifications benefitting DDT&E, and later production.
- Early RBS R&D, and the Upper Stage are un-affected.

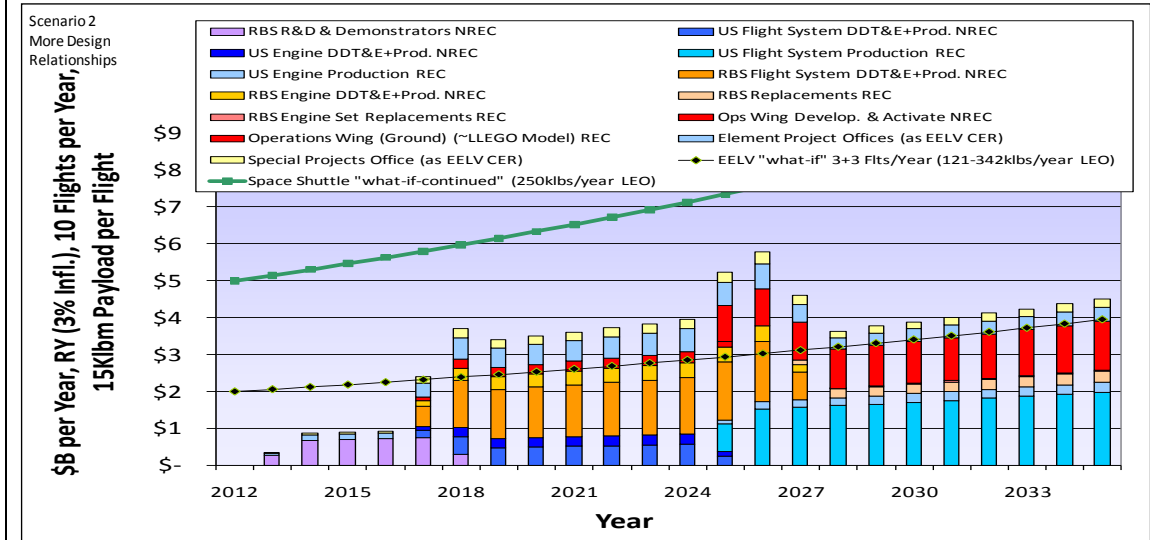


Figure 9: Scenario 2 Life-Cycle Relations

- Scenario 3: The reliability of the reusable booster is increased.
- Increases in up-front costs.
- More test/fail/fix/fly/re-design/learning cycles. *US learned too...*
- Benefits later, in production & wing ops & missions.

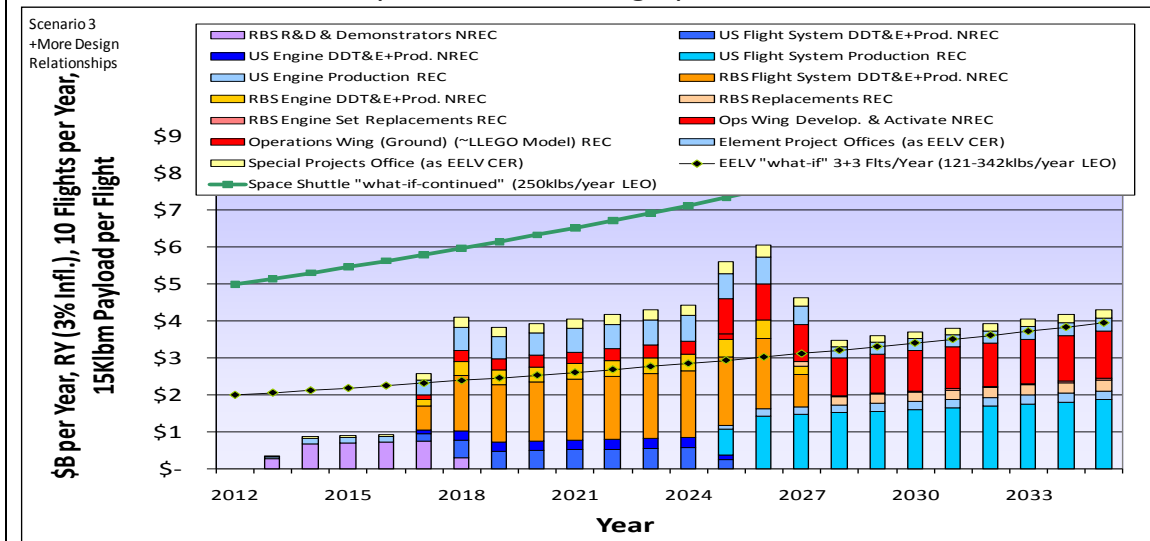


Figure 10: Scenario 3 Life-Cycle Relations

- **Scenario 4: Process & Practice improvements in the operations wing.** Significant process reinventions, new ways of doing business.
 - Per functional definitions, includes both contractor & blue-suiters.
 - These require up-front investment.

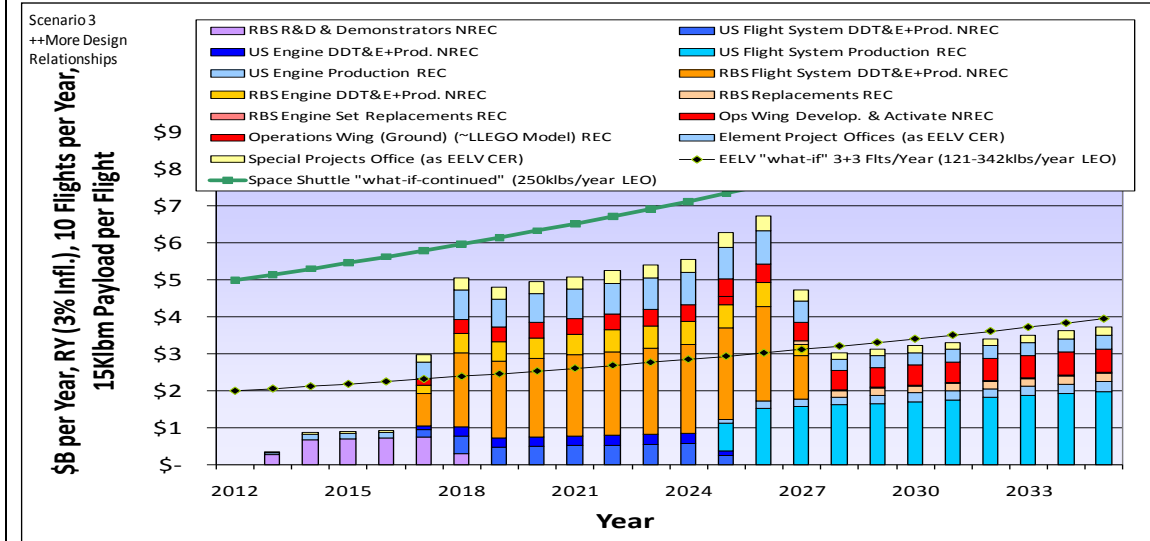


Figure 11: Scenario 4 Life-Cycle Relations

An RBS system design can vary from the complex to the simpler, with parts count, number of engines, number of sub-systems, and so on as the simplest and most straightforward indicator of complexity. Inherently, there will be limitations to the amount of simplification that any system (be it an RBS, an airplane, an automobile, a consumer media device, an enterprise process, etc) can achieve while still adding ever increasing capability to meet a users desires (known or unknown). Functionality breeds complexity over time.

Reliability must be introduced into the equation to balance a system. Technology maturity can offset complexity, as it must, against ever-increasing desires in functional capability. To go farther, faster, more often, usually requires more parts. Reliability allows the cost, management, and risks of the systems to stay ahead of the game. Reusability can be thought of as a means to this end, with reusability design implementation of reliability, and the design-life of the system is "greater than one". Test, fail, fix and re-design cycles buy reliability, as do demonstrators on smaller scales, continued production at a pace that breeds learning, and reduces variance. This affects up-front development costs for all that which remains after simplifying to the maximum extent consistent with functionality.

Lastly, accomplishing the movement of material and information that runs a system (it's development, production, or recurring operations) can be accomplished in many ways, some more efficient than others. Government or contractor, prime or small business, assembler or supplier, tangible part, seal, engine or intangible information, work document, instruction, schedule or manual – there are ways of doing business that define and drive the productivity and the costs of all these (in development, production, or operations). This last variable has been added into this modeling experiment as the series of Supply Chain functions from the LLEGO model, with this aspect founded on the ⁹SCOR model, but propagated through-out the phases of the programs life-cycle in the modeling.

SUMMARY AND CONCLUSIONS

- Methodology promising: Shows a means to take tangible design or process decisions that are part of any decision-making early on and explore their cost effects across phases of the life-cycle.
 - The step “magic happens here” is avoided.
- Preliminary indications are consistent with a previous AoA, where “improvements in systems engineering” were identified as a major cost driver.
 - The analysis here goes further – into many indirect process/practice functions, as well as the systems engineering, simplifications, and reliability needs.

FUTURE WORK

- While the scenarios identified may have shown very promising operations costs and productivity, well linked to why such outcomes are credible (design, reliability, or process/practices), the up-front costs continue to be a challenge. More effort and refinements in the model/method should overcome this challenge. This will identify scenarios with lower development and acquisition costs, linked to tangible, actionable drivers that still benefit operational outcomes.
 - Emphasize forward linkages, how tangible R&D measures can lower near term non-recurring costs.
- Apply the method to larger, 40-60K lbm payload to orbit, RBS configurations currently in consideration as potential follow on systems to the current Expendable Launch Vehicle fleet.
- The 2nd / upper stage has mostly been ignored in linking through and through many of the cost drivers that relate to improvements across the life-cycle. In a future exercise, the 2nd / upper stage of the RBS would be attacked, looking to extend the promising cost connections and improvements that apply to the RBS to this expendable element as well.
- The hybrid model used here would be enhanced, built on, or modified, to simplify or automate the input and analysis process. This enhanced version would focus on highlighting the connections between complexity, reliability/maintainability, and process/practices, across the different life cycle phases. Locating the best combination of design features that credibly connect both to lower up-front development costs as well as productive, affordable operations, should be made easier with a more refined tool-set.
 - Inclusive of addressing how these connections (for example, mission operations process and practices, etc) may or may not apply to the EELV cost comparison points, so as to develop a better understanding of distinguishing factors.
- The variable of time should have a greater emphasis in subsequent analysis. The current LLEGO model does have a series of time calculations/components to automatically maintain consistency between the effort estimated, the turn-time, and work in progress. Nonetheless, more visibility into this important variable is required; especially regarding RBS fleet operations, replacement rates, and learning/production rates.
- Forward work should emphasize rigorous ground-rules and assumptions, configuration data, and basis of all estimates. Such exercises best establish ¹⁰credibility by varying assumptions and recalculating outcomes to see how sensitive these outcomes may be to the assumptions.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the support and feedback of:

- Jason Mossman, Senior Aerospace Engineer, Applications and Assessments Branch, Propulsion Directorate, Air Force Research Lab, Edwards Air Force Base, California.
- Greg Moster, Aerospace Engineer, Air Force Research Lab, Wright-Patterson Air Force Base, Ohio.
- Carey McCleskey, NASA Kennedy Space Center, Engineering & Technology Directorate.

REFERENCES

1 "Defense Acquisitions, Assessments of Selected Weapon Programs", Government Accountability Office, 2008. GAO-11-233SP.

2 "NASA, Assessments of Selected Large-Scale Projects", Government Accountability Office, 2009. GAO-09-306SP.

3 Dean, E. B. (1990). "The Design-to-Cost Manifold," presented at the International Academy of Astronautics Space Systems Cost Estimation Methodologies and Applications, 10-11 May, San Diego CA, IAA-CESO-11(90).

4 Koelle, D.E., Handbook of Cost Engineering for Space Transportation Systems with TRANSCOST 7.1, 2003.

5 Launch & Landing Effects Ground Operations model, NASA Kennedy Space Center, URL viewed 10/29/11 at: http://science.ksc.nasa.gov/shuttle/nexgen/LLEGO_main.htm#LLEGO_presentations.

6 KSC/AFRL Reusable Booster System Concept of Operations, available in summary form at: <http://ntrs.nasa.gov/search.jsp?N=0&Ntk=All&Ntt=rbs&Ntx=mode%20matchallpartial>

7 "Return to Launch Site Trajectory Options for a Reusable Booster without a Secondary Propulsion System", by Dr. John Bradford, SpaceWorks Engineering, Inc., Atlanta, GA 30338, and Barry Hellman, AFRL Air Vehicles Directorate, WPAFB, OH 45433, AIAA 2009-6439.

8 Cost Comparison of Expendable, Hybrid, and Reusable Launch Vehicles, by Greg J. Gstatenbauer and Milton E. Franke, Air Force Institute of Technology, Wright-Patterson AFB, OH 45433, and John W. Livingston, Aeronautical Systems Center, Wright-Patterson AFB, OH 45433, AIAA 2006-7211

9 Supply Chain Operations Reference model, SCOR, from the Supply Chain Council, available at: <http://supply-chain.org/scor>

10 Independent Cost estimate of the Space Launch System, Multi-purpose Crew Vehicle and 21st century ground systems programs, Executive Summary of Final report. August 19th, 2011, by Booz Allen Hamilton.